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Small repeating earthquakes and interplate creep around the 2005 Miyagi-oki earthquake (M=7.2)

Naoki Uchida, Toru Matsuzawa, Satoshi Hirahara, and Akira Hasegawa

Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan

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Taking advantage of the feature that creep around an asperity is necessary for the recurrent rupture of the same small asperity (small repeating earthquakes), we have estimated the spatio-temporal distribution of quasi-static slip (creep) around the 2005 Miyagi-oki earthquake (M=7.2) using the distribution of small repeating earthquakes. The creep was detected mainly outside of the coseismic slip areas for the 2005 Miyagi-oki, 1978 Miyagi-oki (M=7.6) and 2003 Fukushima-oki (M=6.8) earthquakes. The creep rates estimated from the recurrence intervals and slip amounts of small repeating earthquakes for 21 years were almost constant for the areas near the western limit of the interplate earthquakes but they varied temporally in the areas nearer to the Japan trench. The changes in the creep rates before and after the 2005 Miyagi-oki earthquake were not significant with the exception of small slip accelerations in some areas near the Japan trench. These results suggest that the plate boundary around the source area for the 2005 earthquake is still mostly locked.

Key words: Repeating earthquake, asperity, slow slip, subduction zone, interplate earthquake.

1. Introduction

The Miyagi-oki region (east off Miyagi Prefecture, NE Honshu, Japan) is known to have hosted five M=7.3–7.5 interplate earthquakes since 1835 (The Headquarters for Earthquake Research Promotion, 2005; Ohtake and Ueda, 2002; Yamanaka and Kikuchi, 2004). Suwa *et al.* (2006) estimated the interplate slip-deficit rate (backslip rate) in this region from GPS data for the period from 1997 to 2001; their results indicated that the plate boundary in the region was almost 100% locked during the period. The 2005 Miyagi-oki earthquake (M=7.2) occurred in this region on August 16, 2005, and it has been estimated that it ruptured a part of the source area of the 1978 Miyagi-oki earthquake (M=7.6) (Okada *et al.*, 2005; Yaginuma *et al.*, 2006). It is therefore important to determine the nature of the spatio-temporal evolution of plate-boundary coupling in this area.

Repeating earthquake analysis is a powerful tool for estimating the quasi-static slip on the plate boundary (Ellsworth, 1995; Nadeau and McEvilly, 1999; Igarashi *et al.*, 2003; Uchida *et al.*, 2003; Matsubara *et al.*, 2005). Its advantage over GPS data analysis is that slipped region can be precisely located and that longer term data are available.

In the present study, we estimate cumulative slips for small repeating earthquakes assuming that they equivalent to the quasi-static slip histories in the surrounding areas on the plate boundaries (Igarashi *et al.*, 2003; Uchida *et al.*, 2003).

2. Data and Method

We used digital seismograms recorded by the microearthquake observation network of Research Center for Prediction of Earthquakes and Volcanic Eruptions, Tohoku University, for the period from July 1984 to January 2006. The sampling frequency was 100 Hz, and most of the seismometers were of the 1-Hz velocity type. In total, we searched about 10,000 shallow (depth$<$70 km) earthquakes with magnitudes of 2.5 or larger.

Small repeating earthquakes are identified based on the similarity of the seismograms. We calculated the coherence of waveforms for events whose epicentral separations were less than 30 km. The time windows for the seismogram analysis were set at 0–40 s from the P-wave arrivals. This time window always contains the S phase, which guarantees that the waves have the same S-P time (i.e. the same location) if they have high coherence. We considered an earthquake pair to be repeating earthquakes when the averaged coherences at 1–8 Hz were larger than 0.95 at two or more stations. We then linked a pair (group) of repeaters with another pair (group) if the two pairs (groups) shared the same earthquake.

Cumulative slip was estimated using the same procedure as that described by Uchida *et al.* (2003, 2004). The slip for each small repeating earthquake was estimated based on the following relationship between the seismic moment (Mo; dyne·cm) and fault slip (d; cm) (Nadeau and Johnson, 1998).

$$\log(d) = -2.36 + 0.17\log(M_0) \quad (1)$$

This empirical relationship was obtained from shallow repeating earthquake data in California. Igarashi *et al.* (2003), and we confirmed that this slip estimate is consistent with the slip estimated from the relative plate motion

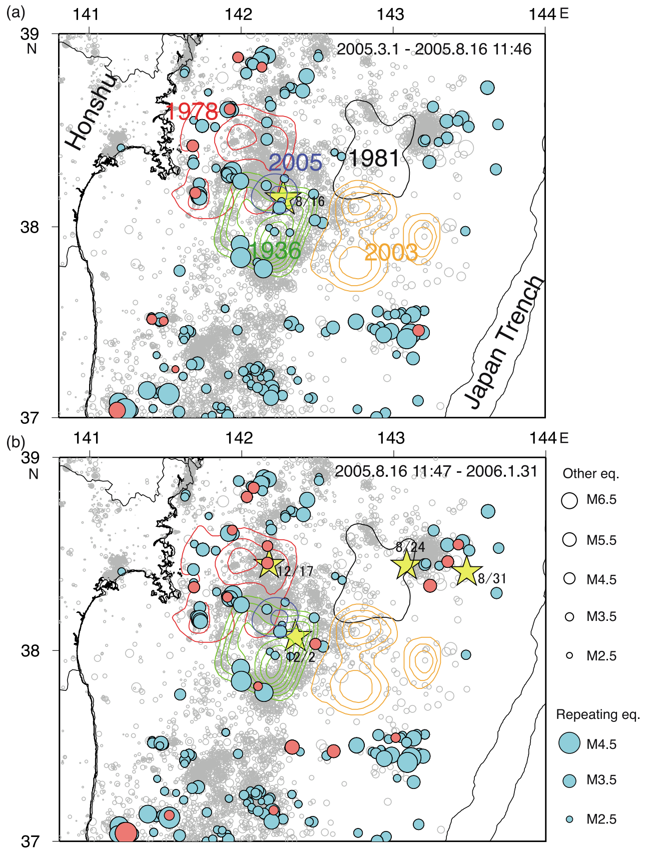

Fig. 1. Distribution of small repeating earthquake groups (blue circles) from July 1984 to February 2005. Orange circles indicate the small repeating earthquake groups that showed activity for the period 5.5 months before the 2005 earthquake (a) (from 1 March 2005 to 11:46 16 August 2005 (JST)) and for the period of 5.5 months after the 2005 earthquake (b) (from 11:47 16 August 2005 to 31 January 2006). Thin contours show the coseismic slip distributions for the 1936 M=7.5 event (green contour), 1978 M=7.6 event (red contour), 1981 M=7.0 event (black contour), 2003 M=6.8 event (orange contour) and 2005 M=7.2 event (blue contour) (Yamanaka, 2003; Yamanaka and Kikuchi, 2004; Yaginuma *et al.*, 2006). Stars denote the hypocenters with a magnitude 6 or larger. Gray circles show the earthquakes shallower than 70 km for the period from January 2005 to January 2006.

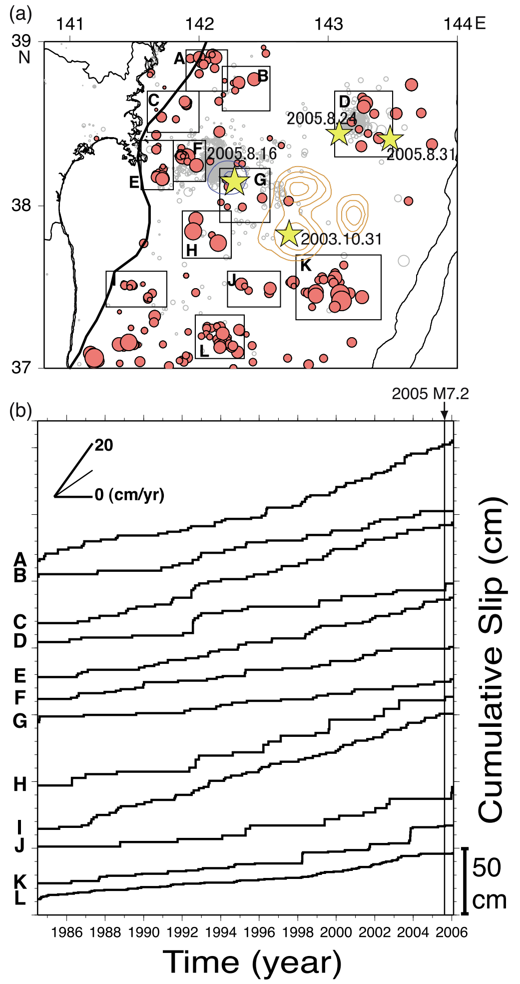

Fig. 2. Averaged cumulative slips of small repeating earthquakes for the period from 1984 to January 2006. (a) Distribution of small repeating earthquakes (orange circles) and sampling windows (rectangles) within which we estimated the averaged cumulative slip. The bold line denotes the western limit of low-angle thrust earthquakes (Igarashi *et al.*, 2001); the thin orange and blue contours are the coseismic slip distributions for the 2003 M=6.8 event and 2005 M=7.2 event, respectively (Yamanaka, 2003; Yaginuma *et al.*, 2006) (b) Averaged cumulative slips for the small repeating earthquake groups in the windows shown in (a). The vertical line marks the time of the M=7.2 earthquake of 16 August 2005.

and the time intervals between repeating earthquakes using data for several interplate events close to the shore of NE Japan. The seismic moment was estimated from the following relationship between the moment and magnitude (M) (Hanks and Kanamori, 1979).

$$\log(M_0) = 1.5M + 16.1. \qquad (2)$$

In this calculation, we used magnitudes determined by the Japan Meteorological Agency. Cumulative slip of each group was then estimated by summing the slip of earthquakes belonging to the group.

3. Distribution of Small Repeating Earthquakes

Figure 1 shows the distribution of small repeating earthquakes around the 2005 Miyagi-oki earthquake. Blue circles show the centroids of repeating earthquake sequences, orange circles indicate the centroids of repeating earthquake sequences that were active during the period 4.5 months before (Fig. 1(a)) and after (Fig. 1(b)) the 2005 event, yellow stars show large earthquakes (M≥6) during this period. The contours denote coseismic slip distributions for the 1978 Miyagi-oki earthquake, the 1981 M=7.0 event, the 2003 M=6.8 event (Yamanaka and Kikuchi, 2004) and the 2005 M=7.1 event (Yaginuma *et al.*, 2006). Regions of large coseismic slip are considered to be asperities (Here, we use the word 'asperity' as the name of region which shows a large slip at the earthquakes and is almost locked in the interseismic period). Most of small repeating earthquakes are distributed outside of these asperities on the plate boundary. Some small repeating earthquakes occurred after the 2005 event (orange circles in Fig. 1(b)) and are distributed near the epicenters of the large earthquakes (yellow stars in Fig. 1(b)).

4. Temporal Change in Creep

Figure 2(b) shows the averaged cumulative slip for small repeating earthquake groups. We averaged the cumulative slip for all of the groups in each rectangle shown in

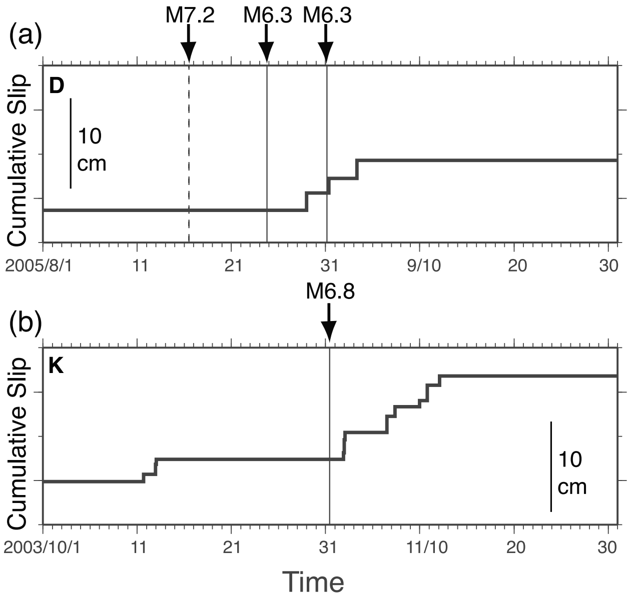

Fig. 3. Averaged cumulative slips for regions D (a) and K (b) for the periods of 2 months around the occurrences of large earthquakes. The occurrence times of major nearby earthquakes are shown by vertical lines and arrows. The dashed vertical line shown in (a) is the occurrence time of the 2005 Miyagi-oki earthquake.

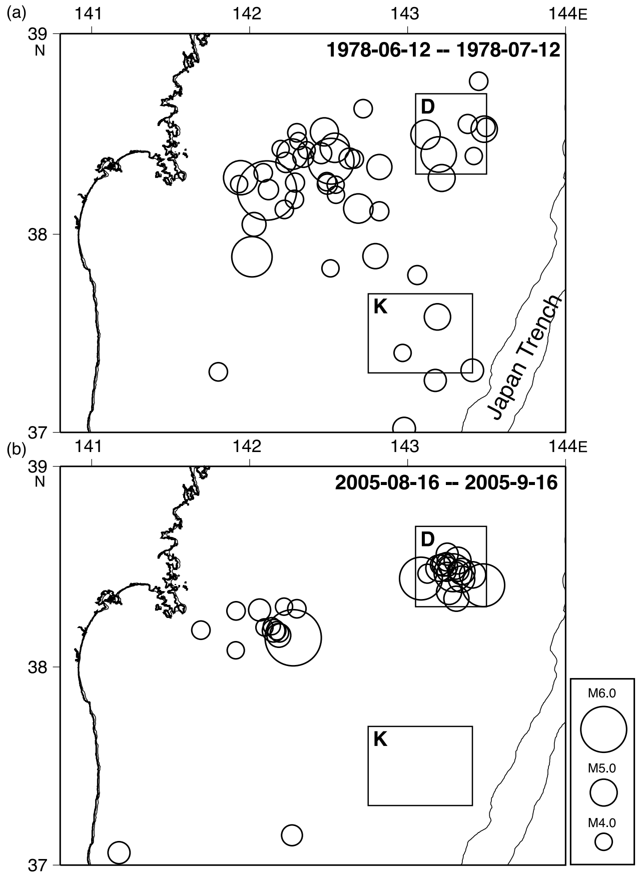

Fig. 4. Aftershock distributions of (a) the 1978 M=7.4 and (b) the 2005 M=7.2 Miyagi-oki earthquakes. Earthquakes with M≥4 and shallower than 60 km for the period of 1 month after each main shock were plotted. Two rectangles labeled D and K are the same as those shown in Fig. 2(a). The hypocenters were determined by Tohoku University and the Japan Meteorological Agency for Fig. (a) and (b), respectively.

Fig. 2(a); the results are presented in Fig. 2(b). Note that there may be an undersampling of some repeating earthquakes before 1992 because the waveform database may have been incomplete. The cumulative slip of small repeating earthquakes (creep) increases with an almost constant rate for most of the region near the western limit of the interplate earthquakes (regions A, C, E, and I). On the other hand, the regions near the Japan trench (regions D and K) show some temporal fluctuations in terms of creep rate. The regions in-between these regions (B, F, G, H, J and L) show relatively low slip rates. The creep-rate change after the 2005 event (vertical line) is insignificant, except for region D where two other M=6.3 earthquakes occurred.

Figure 3(a, b) shows the cumulative slips for the period 2 months before and after some large events within the regions D and K, respectively. In region D, slip was estimated after the first M=6.3 event near the Japan trench, as shown in Fig. 3(a). In region K, slip was estimated both before and after the 2003 M=6.8 event, but the slip after the event is larger than the before (Fig. 3(b)). These observations show the existence of creep acceleration in these regions after the occurrence of large nearby earthquakes.

5. Discussion

The small repeating earthquakes in this study are distributed mainly outside the asperities for large (M=6.8–7.6) earthquakes (Fig. 1). This suggests that the creep is the dominant form of slip behavior outside the asperities. There were 10 and 19 small repeating earthquakes for the period of 5.5 months before and after the 2005 event, respectively (Fig. 1). Therefore, the number of small repeating earthquakes increased after the 2005 event. However, the small creep acceleration, with the exception of that for region D, was not so significant as that for the long-term (21 years) slip history, as shown in Fig. 2. This shows that the creep acceleration near the 2005 event was very weak and therefore could not be detected by means of a small repeating earthquake analysis and that such weak creep accelerations have probably occurred frequently during the 21-year period under discussion.

Miura *et al.* (2006) performed a GPS data analysis to show that the afterslip of the 2005 earthquake was distributed mostly to the south of the coseismic slip area and that the maximum afterslip was as small as about 5 cm. This slip is too small to be detected by small repeating earthquake analysis because the slip for the smallest repeating earthquake analyzed here (M=2.5) is about 10 cm.

The absence of a large afterslip for the 2005 event is peculiar compared to the significant afterslips reported for large interplate earthquakes along the Japan trench. For example, the moments for the afterslips following the 1994 Sanriku-oki earthquake (M=7.6) and the 1989 Sanriku-oki earthquake (M=7.1) were estimated to be almost the same as the coseismic slips (Heki *et al.*, 1997; Nishimura *et al.*, 2000; Kawasaki *et al.*, 2001). As shown in Fig. 1, asperities (coseismic slip areas) for large (M=6.8–7.6) earthquakes are densely distributed in the Miyagi-oki region, and the regions between the asperities are narrow. The 2005 event was estimated to have ruptured only the southeastern part of that of the 1978 event (Yaginuma *et al.*, 2006). Furthermore, the interplate coupling estimated from GPS data is high in this region (Suwa *et al.*, 2006). This lack of a large afterslip of the 2005 earthquake was possibly due to the strong locking around the coseismic slip area for the earthquake.

Increased seismic activity near the Japan trench was observed not only after the 2005 earthquake but also after the 1978 Miyagi-oki earthquake, as shown in Fig. 4. The 1-month aftershock distributions for the 1978 Miyagi-oki earthquake (Fig. 4(a)) and the 2005 earthquake (Fig. 4(b)) are similar to each other, with the exception of those for the area near the region K where the boundary had already slipped in 2003. The activity of small repeating earthquakes in region D after the 2005 M=6.3 earthquake and in region K after the 2003 M=6.8 earthquake shows that there were creep accelerations for those periods. Therefore, unsteady slip in the regions near the Japan trench is probably prone to being triggered by earthquakes in the deeper part of the plate boundary, such as the 1978 and 2005 earthquakes.

6. Conclusions

Spatio-temporal changes in the interplate creep off-Miyagi, Japan were investigated using a 21-year history data set of small repeating earthquake. The small repeating earthquakes were distributed mainly outside the coseismic slip areas for large earthquakes, showing that fault creep is the dominant mode of slip outside of the coseismic slip areas. The estimated creep rate change before and after the 2005 Miyagi-oki earthquake was not significant, with the exception of that for the near-trench region where two M=6.3 events occurred after the 2005 earthquake. These results suggest that the plate boundary around the source area for the 2005 earthquake is still mostly locked. We also found that some seismic activity and creep rate fluctuations in the region near the Japan trench are associated with the interplate earthquakes in the deeper part of the plate boundary.

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N. Uchida (e-mail: uchida@aob.geophys.tohoku.ac.jp), T. Matsuzawa, S. Hirahara, and A. Hasegawa